The Optimal Ankle Foot Orthosis

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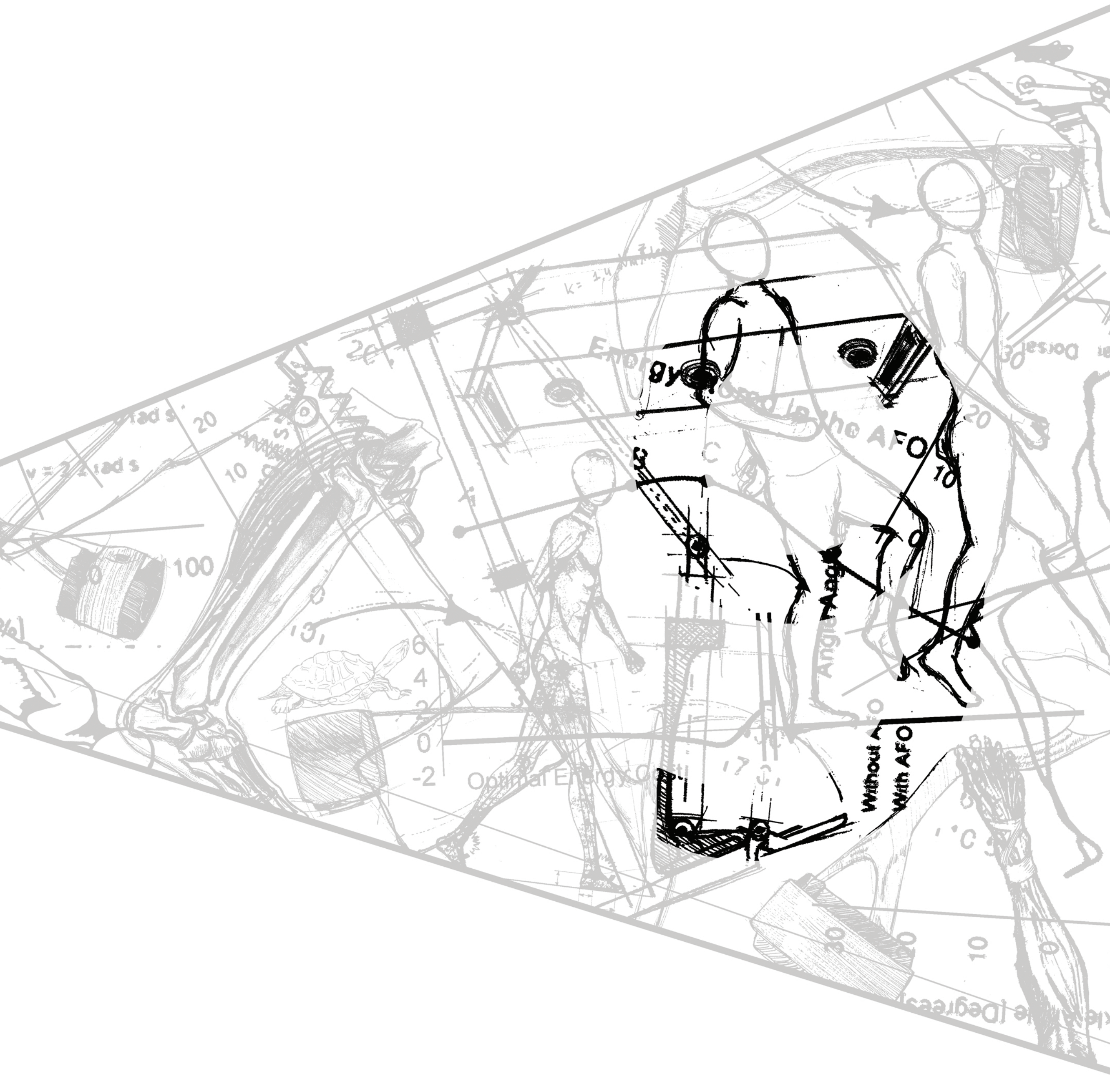
Summary



SUMMARY

Stroke, multiple sclerosis and partial spinal cord injury are central neurological disorders with a high prevalence in western society. Many patients suffering from these central neurological disorders have a reduced walking ability, which has a high impact on daily living. To restore walking ability, Ankle Foot Orthoses (AFOs) are frequently prescribed. However, it is not known which mechanical properties an AFO should hold in order to promote walking ability the most. In this thesis a new method to determine the mechanical AFO properties was proposed. Subsequently, this method was applied to evaluate mechanical AFO functioning, and to determine which mechanical AFO properties should be chosen to promote walking ability the most. Specifically, the aim of this thesis was to study the effect of variations in mechanical AFO properties on mechanical AFO functioning and walking ability in patients suffering from central neurological disorders. The clinical prospect was to define a method of AFO prescription that maximizes the functional benefit obtained from the AFO.

In Chapter 2, a new method to measure the mechanical AFO properties was introduced, and its reliability was assessed. Mechanical AFO properties were defined as the stiffness and neutral angle around the ankle and forefoot joints. A device named BRUCE was designed, based on multidisciplinary consensus. The device replicates a human leg, and is manually driven. It continuously registers (replicated) joint configurations, and forces exerted by the AFO onto the device. From this information, neutral angles and stiffnesses around the ankle and forefoot joints can be determined by means of a linear fit. The reliability of these mechanical AFO properties was studied by repeatedly measuring four different AFOs, and the assessment the resulting inter-session, intra-session, and inter-observer errors. This reliability study revealed that ankle and forefoot stiffness could be measured with very high reliability (ICC= .98-1.00), and that ankle and forefoot neutral angles could be measured with reasonable reliability (ICC =. 79-.92). Measurement error in the neutral angles could mainly be attributed to the difference in testers (i.e. the person operating the device). With a fixed tester, excellent reliability was obtained (ICC = .99-.99). We concluded that with the introduction of the BRUCE device, it is now possible to determine the mechanical AFO properties in a reliable, yet clinically feasible manner.

In Chapter 3, we used the information obtained with the BRUCE device to evaluate the functioning of compliant AFOs prescribed to overcome a dropped-foot (i.e. insufficient activity of the ankle dorsal-flexors in mid-swing). We performed an evaluation of the mechanical functioning of the AFO and an evaluation of the effects of the AFO at activity level. The change in energy cost of walking induced by the AFO was used as a measure of benefit at activity level. We hypothesised that any poor effects of the AFO at activity level would be related to insufficient mechanical contribution of

the AFO during the swing phase, or unwanted constraining of the ankle during the stance phase. In seven patients with stroke or multiple sclerosis, we determined changes in energy cost induced by the AFO, compared to walking without an AFO. In addition, a 3D-instrumented gait analysis was performed, and the mechanical AFO properties were measured to calculate the mechanical contribution of the AFO. The results demonstrated that the AFOs of 0.19 Nm deg^{-1} stiffness were sufficiently stiff to effectively support the foot in swing, without hampering the ankle during stance. For the whole group there was a significant improvement in walking speed and energy cost (12%). However, the AFO had no functional benefit in terms of a reduced energy cost of walking for three patients, who coherently demonstrated no pathological plantar flexion during swing without their AFO. Although it could not be ruled out that these patients may have obtained benefit from the AFO over the course of a whole day, this underlined the importance of a well-considered indication for this type of AFO. We concluded that the AFO was beneficial at activity level when the mechanical AFO properties met the need to support the patient's mechanical deficiencies.

In Chapter 4, we used the information obtained with the BRUCE device to evaluate the functioning of spring-like AFOs prescribed to overcome a reduced ankle push-off in patients with stroke or multiple sclerosis. To compensate for a reduced ankle push-off, these patients perform work at the hip, resulting in an inefficient walking pattern and an elevated energy cost of walking. To overcome the reduced ankle push-off, spring-like carbon-composite AFOs are often prescribed. These AFOs store energy as from mid-stance, and return this energy at the end of the stance phase. We expected that the energy returned by the AFO would support ankle push-off and reduce the elevated energy cost of walking. We measured the energy cost of walking, 3D kinematics, joint powers, and joint work during gait, with and without the AFO, in 10 patients with multiple sclerosis or stroke. The mechanical characteristics of the AFO were measured, and used to calculate the contribution of the AFO to the ankle kinetics. We found a significant decrease of 9.8% in energy cost of walking when walking with the AFO. The range of motion and the net work around the ankle decreased, whereas positive hip work increased when walking with the AFO. The total net work in the affected leg remained unchanged. The AFO accounted for 60% of the positive ankle work, which reduced the total amount of work performed in the affected leg by the patients by 11.1%. We concluded that the decrease in energy cost for neurological patients when walking with a spring-like AFO is not induced by an augmented net ankle push-off, but by the AFO partially taking over ankle work.

In Chapter 5, we used a simulation model to investigate whether there is an optimal stiffness for spring-like AFOs at which gait is most efficient. Specifically, the aim of Chapter 5 was to study the effects of variations in AFO stiffness on the amount of energy stored in the AFO and on the energy cost of walking. We developed a two-dimensional forward-dynamic walking model, with a passive spring at the ankle representing the AFO, and two constant torques at the hip for propulsion. We varied the AFO stiffness, while keeping speed and step-length constant, and found an optimal stiffness in terms of energy cost of walking. Furthermore, we found that energy cost decreased with increasing AFO energy storage, but the most efficient gait did not occur with maximal energy storage. With maximal storage, push-off occurred too late to reduce the impact of the contralateral leg with the floor. Maximum energy return prior to heel strike was also suboptimal, because push-off occurred too early and its effects were subsequently counteracted by gravity. The optimal AFO stiffness resulted in significant push-off timed just prior to contralateral foot strike, and led to greater ankle plantar flexion velocity just before contralateral foot strike. We concluded that energy cost can be reduced by the appropriate choice of AFO stiffness. Moreover, we concluded that energy cost of walking with a spring-like AFO depends not only on the amount of energy stored and returned by the AFO, but also on the timing of the energy return.

In Chapter 6, we studied the effect of systematic variations in AFO stiffness on the energy cost of walking in patients with a reduced push-off due to stroke, multiple sclerosis or partial spinal cord injury. In 8 patients 3D kinematics, joint power, and joint work were measured in 6 conditions: walking without an AFO and walking with five AFOs of increasing stiffness (i.e 0.5, 1.3, 1.7, 3.2, and 5.4 Nm deg^{-1}). The mechanical characteristics of the five AFOs were measured, and used to calculate the contribution of each AFO to the ankle kinetics. We observed an average optimal AFO stiffness of 1.40 (.41) Nm deg^{-1}, at which the energy cost was minimal. The optimal AFO stiffness appeared to be the best compromise between an increasing amount of work done by the AFO with increasing stiffness, and a decreasing ability to generate push-off, and an increased need to perform work at the hip with increasing stiffness. The average optimal stiffness of 1.4 Nm deg^{-1} may serve as an indication of the optimal stiffness for spring-like AFOs in neurological patients with reduced ankle push-off.

In Chapter 7, we synthesized all previous findings on AFO functioning in the design of an AFO that would theoretically be the most beneficial for the patient. In Chapter 4, we observed that typical spring-like AFOs lower the energy cost by taking over ankle work, despite reducing the net ankle push-off, due to a lowered ankle angular velocity at the same time. Theoretically, an AFO that takes over ankle work while allowing for any voluntary ankle push-off, could be of increased benefit. This concept was embedded in the Klap-AFO, an AFO with a difference in stiffness towards dorsal flexion and plantar flexion. The Klap-AFO is expected to allow for the storage and return of energy by the AFO, without constraining any remaining voluntary ankle push-off. To optimally exploit the Klap-AFO, we suggested an AFO stiffness towards dorsal flexion that leads to the greatest plantar flexion velocity by its energy return. Plantar flexion stiffness should just be high enough to prevent the foot from plantar flexion in swing. The Klap-AFO is an example of how thorough mechanical analysis of AFOs can lead to new developments in the fabrication and prescription of AFOs.

In Chapter 8, we discussed the methodological issues associated with our research, emphasized the main findings, and elaborated on the implications for future research and clinical practice. We reflected on the consequences of our methodological choices with regard to the inclusion, study design, outcome measures, and mechanical appraisal of the AFO. We concluded that our methodological choices had no significant influence on the main findings. The main findings were:

1) We developed a new device called BRUCE, to measure the mechanical AFO properties in a reliable and clinically feasible manner. After the mechanical characterization of the AFO, its function during gait could be revealed with instrumented gait analysis.

2) We identified the working mechanisms of compliant AFOs to overcome drop-foot gait, and spring-like AFOs to overcome reduced ankle push-off. Specifically, we showed that an 0.2 Nm deg^{-1} AFO is sufficient to support the foot throughout the swing phase without hampering the ankle during stance. We demonstrated that 2.5 Nm deg^{-1}, spring-like AFOs reduce the energy cost of walking by taking over ankle work, rather than by increasing ankle push-off.

3) We theoretically and physically demonstrated the presence of an optimal AFO stiffness at which the energy cost of walking is minimized. Model simulations showed that this optimum depends not only on the amount of energy stored and returned by the spring-like AFO, but also on the timing of this energy return. Physical experiments indicated an optimal AFO stiffness of 1.4 Nm deg^{-1}, which was the best compromise between an increasing amount of ankle work by the AFO with increasing stiffness, and a decreasing ability to generate push-off, and an increased need to perform work at the hip with increasing stiffness.

From the main findings of this thesis we concluded directions for future research. We advocated that the methods introduced in this thesis should be applied in future orthotics research. Furthermore, future research should focus on the mechanical AFO properties besides the stiffness, i.e. the neutral angle at the ankle and the stiffness and the neutral angle at the forefoot. To be able to apply the results of this thesis in a clinical setting, future research should aim to identify factors that can predict optimal AFO properties. With regard to clinical practice, we expect that the mechanical characterization of AFOs using BRUCE will further objectify the process of AFO prescription, and promote better communication between orthotists and physicians. Moreover, the working mechanisms that were identified and the corresponding optimal AFO properties proposed in this thesis can now be applied in clinical practice.